

Airborne Lidar Tracking of Fluorescent
Tracers for Atmospheric Transport and
Diffusion Studies

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16. ABSTRACT Development and validation of transport models for the study of regional acid deposition require improved observations of pollutant transport and dispersion processes. Current methods for tracking air-parcel is limited to constant density surfaces using tetroons or by gaseous tracers requiring the use of in situ aircraft. The feasibility of using an airborne lidar system to observe atmospheric transport and dispersion of fluorescent dye particle (FDP) tracers is promising and was demonstrated for various meteorological conditions and FDP release scenarios in the general area of the Cross-Appalachian Tracer Experiment (CAPTEX) during October 1983. This paper presents some of the results obtained on six case studies, each of which illustrates a unique application of the technique.		
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Airborne Lidar Tracking of Fluorescent Tracers for Atmospheric Transport and Diffusion Studies

Abstract

Development and validation of transport models for the study of regional acid deposition require improved observations of pollutant transport and dispersion processes. No suitable method for air-parcel tracking along nonconstant density surfaces is available. The feasibility of using an airborne lidar system to observe atmospheric transport and dispersion of fluorescent-dye-particle (FDP) tracers was demonstrated for various meteorological conditions and FDP-release scenarios in the general area of the Cross-Appalachian Tracer Experiment (CAPTEX) during October 1983. This paper presents some of the results obtained on six case studies, each of which illustrates a unique application of the technique.

1. Introduction

Anthropogenic pollutants such as acidic precursors, oxidants, and particulates can arrive above a convective mixed layer by convective-cloud venting (Ching *et al.*, 1983, 1984a) or by air-mass convergence. These pollutants are then displaced along paths that are not necessarily horizontal, and can subsequently re-enter the mixed layer by either entrainment or subsidence or in precipitating systems. The development of improved long-range transport models will require consideration of the transport and dispersion processes in both the mixed and free tropospheric layers (Lamb, 1983).

These processes in the free troposphere are not adequately documented or understood, and are generally ignored in current trajectory-calculation schemes and source-to-receptor models. This is primarily due to the lack of adequate measurement techniques or air-parcel-tracking technology for this application. For example, tetroons are set to drift along constant-density surfaces (Booker *et al.*, 1965); however, free tropospheric transport is more likely to occur along isentropic surfaces (Danielsen, 1961). The use of chemical tracers requires in situ sampling by aircraft, but logistical requirements make Lagrangian tracking extremely difficult on long-range transport scales. Thus, adequate and precise verification data to test and validate model-trajectory calculation schemes that (for operational purposes) utilize twice-daily routine soundings from the synoptic-scale network are still unavailable.

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A study was initiated to evaluate the possibility of using an airborne lidar system to remotely track and map the concentration distribution of fluorescent-dye particles (FDPs) injected into the atmosphere (Ching *et al.*, 1984b). The study consisted of 1) ground testing to establish optimum lidar configuration, 2) local airborne testing to evaluate methods of injecting required FDP concentrations for long-range transport measurements, and 3) demonstration tests for various meteorological conditions and FDP-release scenarios.

2. ALPHA-1/FDP Technique

The ALPHA-1 airborne lidar was constructed for the Electric Power Research Institute (EPRI) as a two-wavelength system for observing distributions of aerosol concentrations in the atmosphere (Uthe, 1983). An Nd:YAG laser and frequency doubler generate 1.06- and 0.53- μm -wavelength radiation. Two independent receivers and data channels simultaneously observe range-resolved atmospheric backscatter and surface-reflected energy at the transmitted wavelengths. The data are plotted in real time on a facsimile recorder as height-distance pictorial displays. As shown by Rowland and Konrad (1979), laser radiation can excite fluorescent-dye particles (FDPs) to emit fluorescent radiation over a wavelength interval separated from the incident wavelength. Therefore, the FDPs can be observed without interference from elastic scattering by background aerosols at the incident wavelength. For the airborne lidar/FDP experiments, one ALPHA-1 receiver was used to observe aerosol elastic backscattering at 1.06 μm , and the other was modified to receive fluorescent light at 0.6 μm while rejecting the backscattered light at 1.06 and 0.53 μm . Thus, simultaneous mapping of an FDP cloud that emits at 0.6 μm , and the atmospheric structure revealed by aerosol gradients, could be achieved with the modified ALPHA-1 system.

The FDP tracers used were transparent organic resin particles containing a dye with a fluorescent orange color (0.6 μm) designated fire orange by the manufacturer.³ Analysis of FDP size by SRI International indicated a particle diameter of about 2 μm . Using the manufacturer-specified particle density of $1.36 \text{ g} \cdot \text{cm}^{-3}$, the fall velocity of these particles in air near the top of the boundary layer is about $0.2 \text{ mm} \cdot \text{s}^{-1}$. Ground-based experiments showed the energy of fluorescent-dye returns to be only about a factor of 4 greater than

³ Day-Glo Color Corporation, Cleveland, Ohio.



FIG. 1. SRI Queen Air aircraft used for ALPHA-1 airborne lidar observations.

the particle's elastic-backscatter cross section. Therefore, for each tracking experiment, a relatively large quantity of FDP material (~ 50 kg) was released as a 0.5–0.75 km diameter cloud of 20–30 m thickness using a cropduster aircraft. Figure 1 presents a view of the twin-engine Queen Air aircraft used to support the ALPHA-1 airborne lidar, and Fig. 2 shows the FDP cropduster and an initial FDP cloud generated below the lidar aircraft for long-range tracking.

3. Case studies

The ALPHA-1/FDP technique was tested for various meteorological conditions and FDP-release scenarios. These tests were conducted in association with the Cross-Appalachian Tracer Experiment, CAPTEX '83 (Clark *et al.*, 1984), as a means to acquire additional meteorological data for analyses of the FDP-tracking results. Each of the six case studies selected for analysis is briefly discussed below, with additional details provided in a technical report (Uthe *et al.*, 1984). Figure 3 shows the FDP-cloud tracks as observed by the ALPHA-1 system for the six experiments.

a. Long-range three-dimensional trajectory

On 14 October 1983, 1802–2305 EDT, an ALPHA-1/FDP experiment was conducted to demonstrate the feasibility of determining with high spatial and temporal resolution the three-dimensional trajectory of a tracer cloud over a distance of several hundred kilometers above relatively complex terrain. Such observations can be used in the study and modeling of air-parcel trajectories and long-range transport in the free troposphere. Approximately 50 kg of fluorescent-dye particles were released as a doughnut-shaped cloud (about 0.75 km in diameter) during cloud-free conditions over Lancaster, Ohio (45 km southeast of Columbus), at 1750 EDT. Release height was 2290 m above sea level (ASL) at nearly 900 m above the mixing layer, and in relatively dry air above



FIG. 2. (a) Loading of FDP tracers and (b) their release by cropduster aircraft.

a subsidence inversion. The ALPHA-1 tracked the FDPs over a distance of 327 km from Lancaster southeastward through West Virginia, over relatively complex terrain, to just across the Shenandoah Mountains. Figure 4 shows the projection of the FDP-cloud trajectory in a vertical plane (lines AB and CD), and Fig. 5 shows its projection in the horizontal plane. The lidar aircraft was refueled at point B, and contact with the FDP cloud was re-established at point C.

The FDP trajectory is compared with an isobaric (line EG) and isentropic (line EF) trajectory calculated by using data from the standard radiosonde network, and with a tetron trajectory at the same altitude. Differences between the FDP trajectory and the calculated trajectories in the vertical and horizontal plane are apparent and indicate that either the air motion is not exactly isobaric or isentropic or that the calculated trajectories are inaccurate because they are based on too sparse a network of upper-air data. The direction and average speed of the tetron trajectory from 1955 EDT to 0043 EDT are the same as those of the FDP trajectory marked by the line CD.

b. FDP cloud-shape experiment

On 16 October, an ALPHA-1/FDP experiment was conducted to establish the feasibility of evaluating tracer-cloud height, shape, and size with high spatial resolution. Such

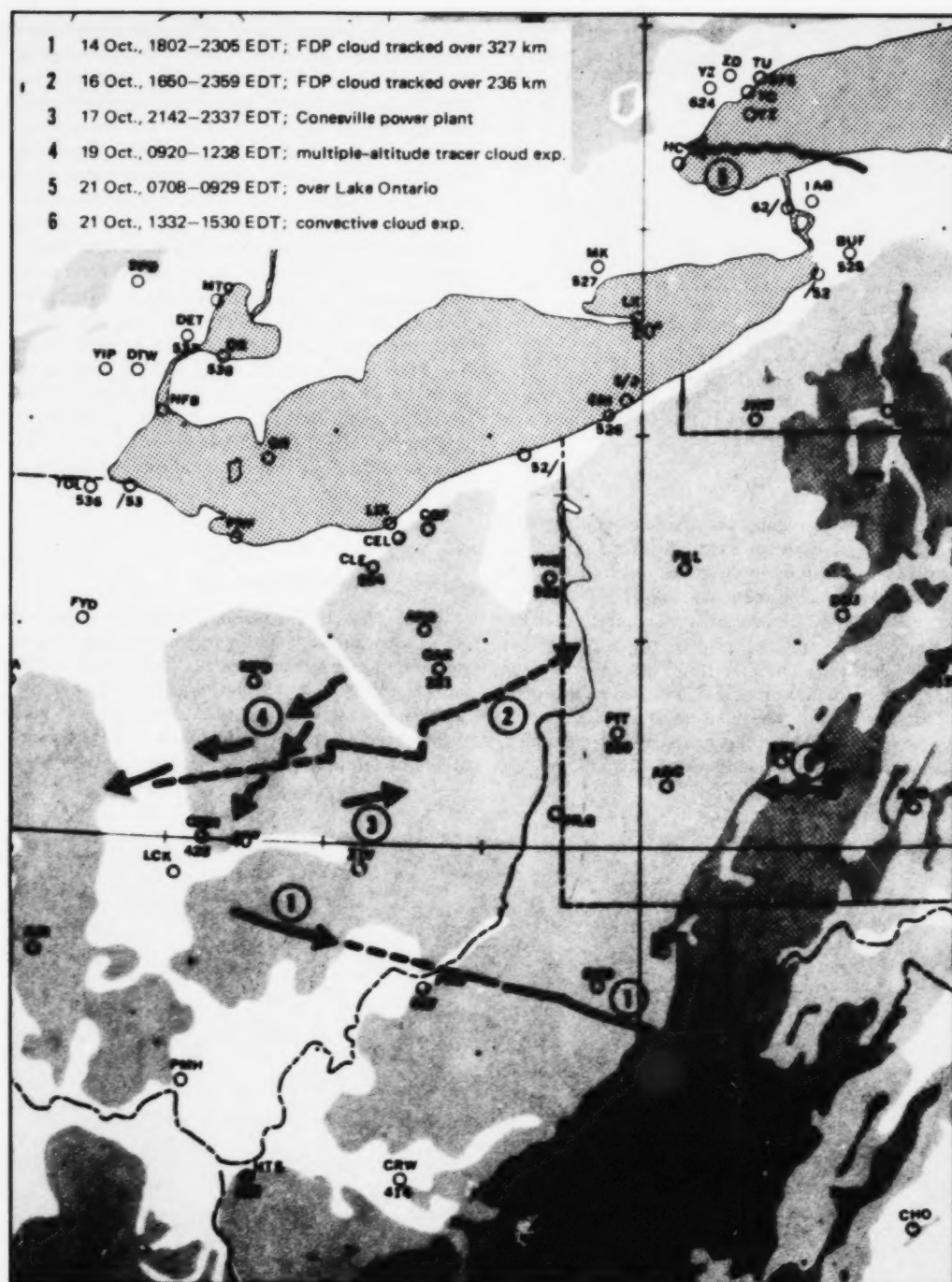


FIG. 3. Geographic locations and horizontal FDP-transport trajectories associated with six ALPHA-1/FDP experiments conducted in the CAPTEX area during October 1983.

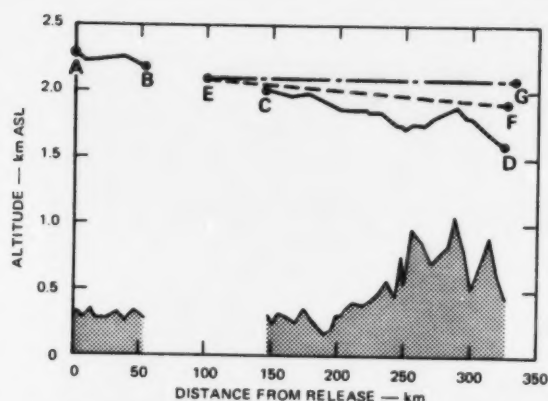


FIG. 4. Vertical plane of observed FDP-cloud trajectory (lines AB and CD) with underlying terrain contour. Lines EF and EG represent computed air-parcel trajectory on the isentropic and isobaric surface, respectively, starting on the FDP-cloud track at point E (1802–2305 EDT 14 October 1983).

data can be used to determine dispersion rates along and transverse to the transport direction of the cloud, and to identify small-scale features in the atmospheric circulation. An FDP cloud was released about 40 km north of Columbus, Ohio, at 1650 EDT. A high-pressure system prevailed in the area. Release height was 2300 m ASL, about 500–800 m above the mixing layer. The FDP cloud was tracked by the ALPHA-1 over a total distance of 236 km through eastern Ohio. Underlying terrain was relatively flat. Using a three-dimensional plotting routine, Fig. 6 presents two computer-generated views of the cloud shape as observed by the

ALPHA-1 during the time period 1845–1908 EDT (about 95 km downwind from release). Figure 6a shows the successive vertical cross-sectional areas obtained by the lidar as viewed from a hypothetical-observer position above and to the front of the FDP cloud. The cross-sectional areas were obtained while flying back and forth along the same flight path during the time period that the FDP cloud was transported across the vertical plane containing the flight path. In a similar way, Fig. 6b presents a view of the successive vertical cross-sectional areas from a position to the side and front of the cloud. It is seen from Fig. 6 that the cloud is about 16 km long, as much as 2 km wide, and 100–200 m thick. The “bend” in the cloud in Figure 6a between cross sections 1 and 5 coincided with the location of a troughline in the wind field. Wave motion is indicated in Fig. 6b. The interesting aspect of this observed transport case is the rapid along-wind stretching of the FDP cloud from its initial 0.75-km diameter circular shape to an elongated shape with an 8-to-1 (16-to-2 km) length-to-width ratio. A second evaluation of cloud shape 150 km downwind of the FDP release (about four hours of travel time) showed that the cloud continued to lengthen to about 30 km long.

c. Power-plant plume experiment

An ALPHA-1/FDP experiment conducted on the evening of 17 October investigated the feasibility of tracking an FDP tracer puff released near a power-plant plume at 500–600 m above ground level. The power-plant plume and the tracer cloud were observed by ALPHA-1 for nearly two hours. The lidar observations were made to show the diffusion of the plume and tracer puff transverse to the transport wind direc-

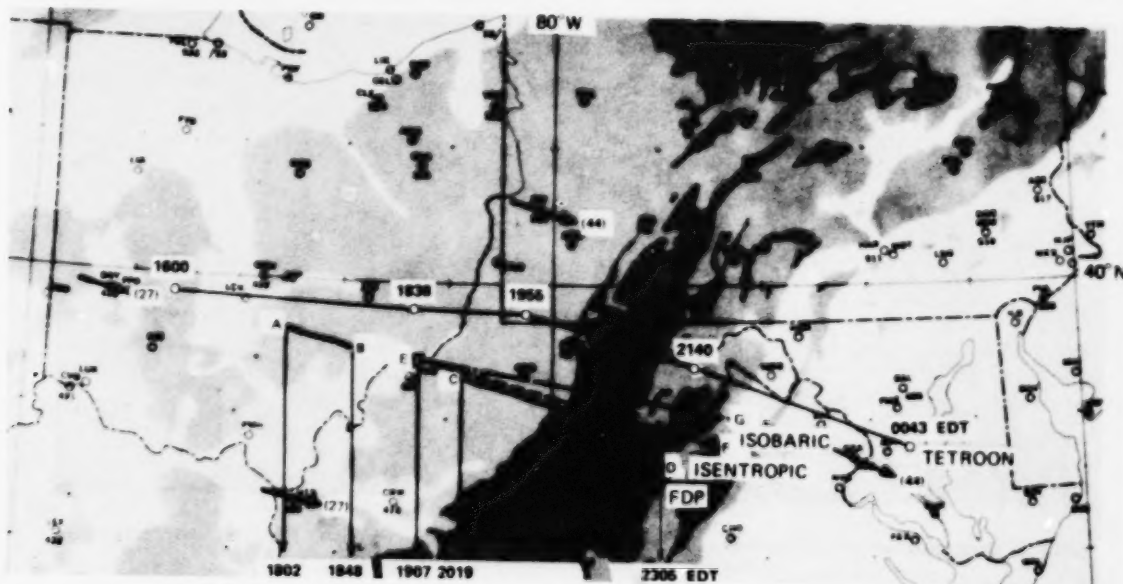


FIG. 5. Observed FDP-cloud trajectory (lines AB and CD), compared with computed isentropic air trajectory (line EF), and isobaric trajectory (line EG). Tetron trajectory is indicated by a solid line.

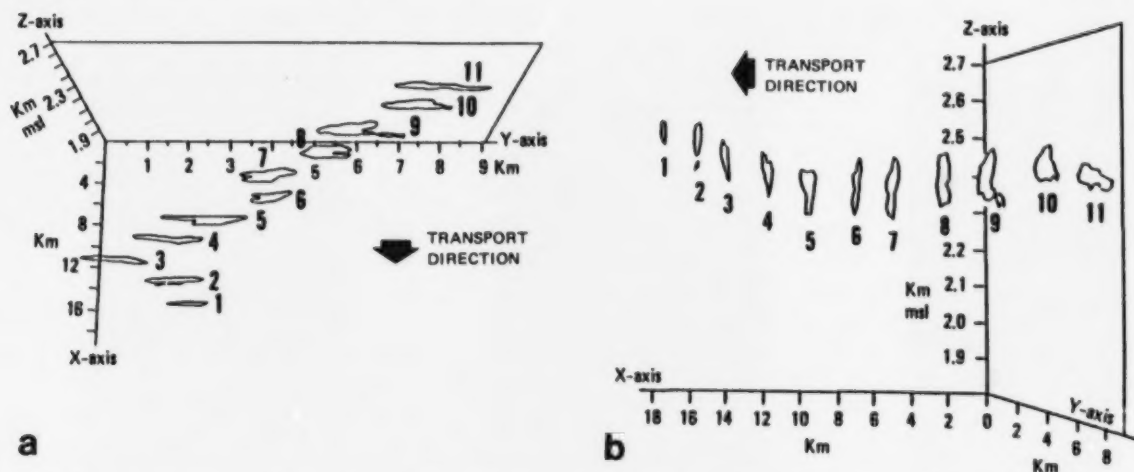


FIG. 6. FDP-cloud structure observed by ALPHA-1 two hours after release at 1845–1908 EDT 16 October 1983. (a) Top view of cross-sectional lidar data along entire FDP cloud length (numbers 1 through 11). Individual lidar cross sections are numbered. (b) Side view of lidar cross sections. Transport direction is along the X-axis.

tion, and to provide information on “puff” dimensions in the downwind direction. The FDP tracer puff was released at the top of the plume of the Conesville Power Plant located about 80 km (50 miles) east of Columbus, Ohio. The release height was 600 m above ground level, which corresponded to the top of the haze layer, as indicated by the lidar data. Winds were southwesterly in advance of a cold front approaching from the west. The experiment took place during darkness, and little or no visual contact was made with either the plume or the tracer cloud. Using the lidar backscatter signals as guidance, the lidar aircraft was directed along flight paths nearly transverse to the transport wind.

Figure 7a shows lidar data of the power plant plume before an FDP release about 1.5 km downwind from the power plant. The plume lies on top of the haze layer, and no fluorescent light from the plume or background aerosols is evident on the fluorescence channel. Figure 7b shows the puff of fluorescent tracer shortly after it was released on top of the plume near 2142 EDT. At the backscatter wavelength of $1.06 \mu\text{m}$, the tracer puff is difficult to locate in the plume background. The fluorescence channel, however, identifies the location and shape of the tracer puff without interference by the plume and the background aerosol. The plume is about 3.7 km wide and the FDP puff is about 300 m wide 1.6 km downwind from the power plant, assuming the aircraft traverse is truly perpendicular to the transport direction. At 2205 EDT (7.7 km downwind), the tracer puff has grown in the transverse direction to 1300 m, as shown by the fluorescence channel data in Fig. 7c. Observations of the type presented in Fig. 7 were recorded by the ALPHA-1 over a two-hour period.

At one hour and 16 minutes after release (20 km downwind), the length of the FDP-tracer cloud was between 2 and 3 km, as estimated from lidar observations made at the same downwind distance while the tracer cloud passed below the aircraft flight level. This indicates that the cloud dimensions in the downwind direction are about the same as the cross-

cloud dimensions. The cross-cloud dimensions increased with two hours’ travel time from about 0.3 km at release to about 4 km at 29 km downwind.

d. Two-cloud experiment

On 19 October, FDP clouds were released at two different altitudes in a northeast-to-southwest wind-flow regime. By tracking the top and bottom tracer clouds, the ALPHA-1 observed a large directional change in the wind between the two altitudes. Individual FDP-cloud observations also showed wind-shear effects and descending motion during the three-hour lidar-tracking period. Such data can be used in studies of the transport and dispersion of plumes. Separate FDP clouds were released at 2200 m and at 1600 m AGL. The transport and dispersion of these two clouds were observed by the ALPHA-1 flying near an altitude of 2700–2800 m AGL for nearly three hours, over a distance of 132 km downwind of the release point. Figure 8 shows the release and tracking area between Columbus and Mansfield, Ohio. The tracer releases took place at nearly the same location (location 1 in Fig. 8). The horizontal trajectories of the top and bottom FDP clouds were observed to diverge. The top cloud followed the tracks indicated by the numbers 2 and 3, while the bottom cloud followed the trajectory indicated by the numbers 4 and 5. At the end of the three-hour tracking period, the two clouds were separated by a horizontal distance of nearly 70 km. This separation with altitude identified a directional change in the horizontal wind equal to 21 degrees. The top tracer cloud descended at a mean value of $4.1 \text{ cm} \cdot \text{s}^{-1}$ and the bottom cloud at a mean value of $1.6 \text{ cm} \cdot \text{s}^{-1}$. These numbers suggest that the subsidence (downward motion) decreased in the direction toward the top of the haze layer (1000–1100 m above ground level) where, most likely, it approached zero.

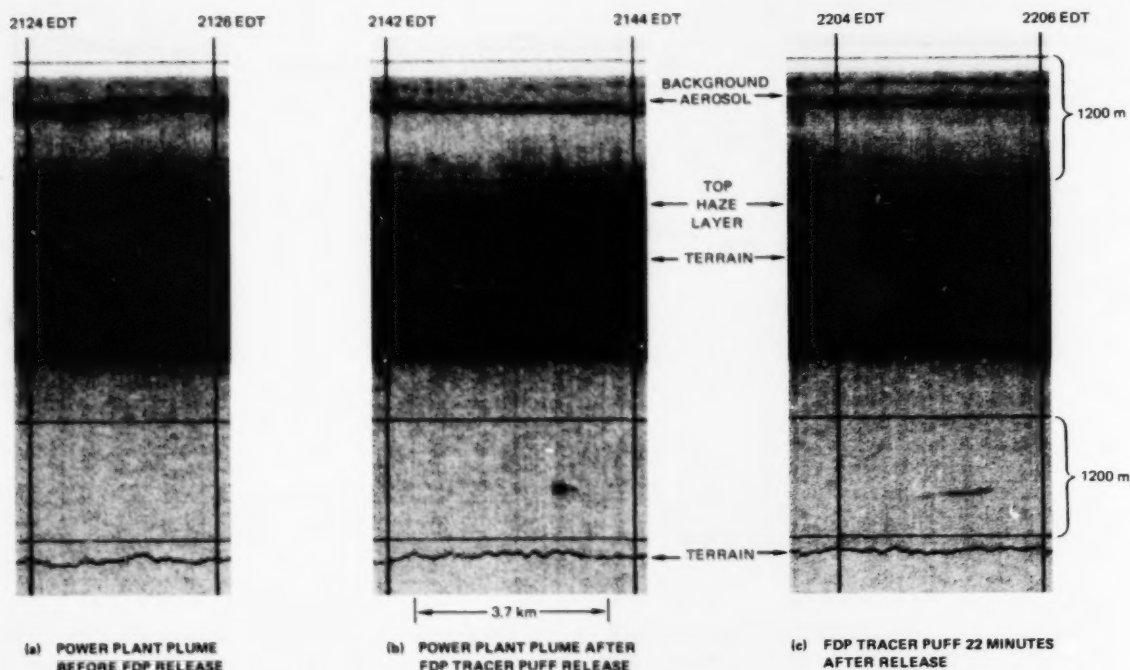


FIG. 7. Samples of lidar data transverse to a power-plant plume recorded during the ALPHA-1/FDP experiment at the Conesville Power Plant east of Columbus, Ohio, on 17 October 1983. Upper part: Elastic backscatter at $1.06 \mu\text{m}$ showing power-plant plume, FDP puff, and background aerosol. Lower part: Fluorescent backscatter; $0.53 \mu\text{m}$ transmitted, $0.60 \mu\text{m}$ received. Aircraft altitude: 2300 ASL.



FIG. 8. Area of ALPHA-1/FDP study of tracer clouds released at two different altitudes below the lidar aircraft at 0920-1238 EDT 19 October 1983. 1: Release location; 2 and 3: Trajectory of top FDP cloud; 4 and 5: Trajectory of bottom FDP cloud. Thin lines with arrows represent mean trajectories with direction in degrees.

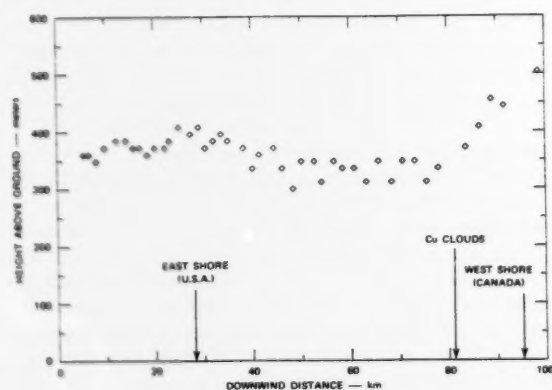


FIG. 9. Altitude above ground level of FDP-tracer cloud observed by the ALPHA-1 during the ALPHA-1/FDP experiment across Lake Ontario on 21 October 1983, 0708 to 0929 EDT. Note descending motion over lake surface and strong ascending motion of FDP cloud as it approaches the west shore during on-shore wind-flow conditions.

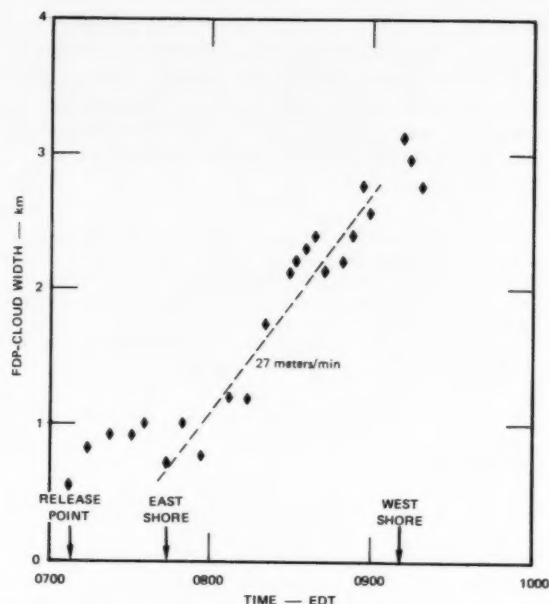


FIG. 10. Size of FDP-tracer cloud transverse to transport direction observed by the lidar as a function of time during the ALPHA-1/FDP experiment across Lake Ontario, 0708 to 0929 EDT 21 October 1983.

e. Lake Ontario transport experiment

On 21 October, a low-altitude FDP tracer cloud was released north of Buffalo, New York, on the east shore of Lake Ontario during easterly wind flow. The tracer cloud was transported across the lake and its dispersion characteristics were observed by the ALPHA-1 for over two hours. The objective of this experiment was to provide observational data on transport and dispersion over water and near a land/water boundary. The FDP cloud was released above a location on the United States shore of Lake Ontario just north of Buffalo, New York. The release was made before sunrise at an altitude of 360 m above ground level. Figure 3 shows the tracer cloud trajectory across the lake from the United States to the Canadian shore over a distance of about 95 km (2.3 hours of travel time). The height of the tracer cloud, as observed by the ALPHA-1 along the cloud trajectory, is shown in Fig. 9. Observed cloud height is presented as a function of distance downwind from the release point. From the release point to the United States shoreline, a slight increase in cloud height (ascending motion) is evident. A descending cloud motion ($1.5 \text{ cm} \cdot \text{s}^{-1}$) is observed along the over-water trajectory. Upon approaching the Canadian shore, a strong upward motion ($10 \text{ cm} \cdot \text{s}^{-1}$) of the tracer cloud occurred, which continued to the shoreline. Cumulus clouds were present in this area and probably were associated with the on-shore flow and solar heating of the land surface two hours after

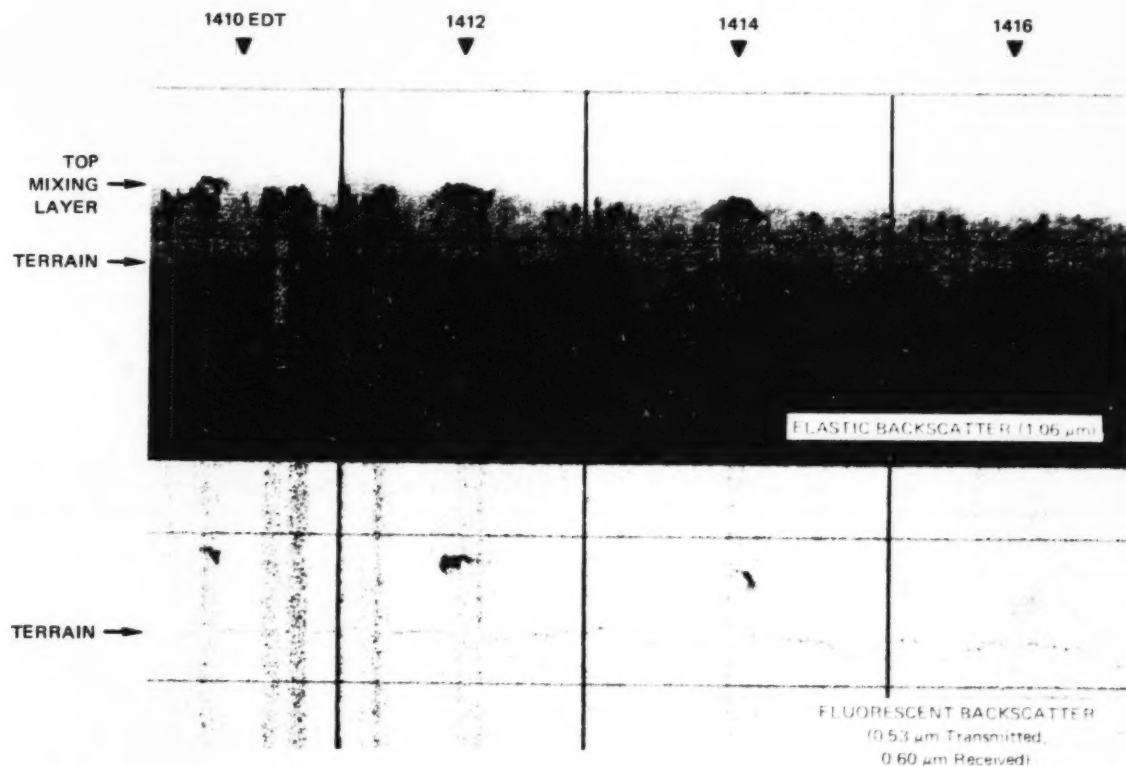


FIG. 11. Six-minute time series of lidar data showing release of FDP near top of cumulus clouds (1410 EDT) and rapid dispersion in the boundary layer at 200 m to 300 m above ground level (1416 EDT) (Convective Cloud Experiment, 21 October 1983).

sunrise. The growth rate of the FDP cloud observed by the ALPHA-1 in a general direction transverse to the east-to-west transport wind is illustrated in Fig. 10. The growth rate is large along the over-water trajectory. By fitting a linear regression to the 15 data points over the lake surface, a mean growth rate of $27 \text{ m} \cdot \text{min}^{-1}$ is obtained.

f. Convective cloud experiments

During the afternoon of 21 October, tracers were released at various positions with respect to convective cumulus clouds. This experiment provided information on the transport and dispersion characteristics of the convective mixing layer. The FDP releases were made in the vicinity and at various altitudes around shallow convective cumulus-cloud fields near Johnstown, Pennsylvania (about 120 km east-southeast of Pittsburgh). Johnstown is located on the western slope of the Allegheny Mountains at an elevation of 2282 feet ASL. According to the radiosonde ascents made at Pittsburgh, the winds in the FDP experiment area were southeasterly at 20–25 knots. Thus, Johnstown was located on the lee side of the mountains. Cloud bases were 500 m and cloud tops were 800–1000 m above ground level. An FDP cloud, which was released in a clear area halfway between the base and tops of surrounding cumulus clouds, rapidly disappeared by turbulent mixing after about four minutes. When an FDP release was made near the base of cumulus clouds, the lidar aircraft flying above the clouds could not monitor the tracer cloud because of the cumulus-cloud-obstructed line of sight. However, the FDP was visually observed to rapidly disperse within the boundary layer.

Figure 11 shows an example of lidar data after FDP tracers were released near the top of the cumulus. The cumulus and mixing layer are shown in the $1.06\text{-}\mu\text{m}$ elastic-backscatter data; the tracer cloud is clearly identified in the fluorescence channel, which blocks the backscattered 1.06- and $0.53\text{-}\mu\text{m}$ radiation from the atmosphere. After release at about 600 m above the underlying terrain at 1410 EDT, the tracer cloud follows a descending trajectory into the turbulent boundary layer where it is rapidly diluted six minutes later at an altitude of 200 m to 300 m above ground level.

4. Summary

The feasibility of using airborne lidar to remotely monitor the three-dimensional distribution of fluorescent-dye-parti-

cle (FDP) tracers in long-range atmospheric transport and dispersion studies has been successfully demonstrated. The technique has great potential for supporting research programs to help address problems related to isentropic transport, cloud venting, boundary-layer and free-tropospheric transport and dispersion, and complex terrain effects.

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References

- Booker, D. R., and L. W. Cooper, 1965: Super pressure balloons for weather research. *J. Appl. Meteor.*, **4**, 122–129.
- Ching, J. K. S., J. F. Clarke, J. S. Irwin, and J. M. Godowitch, 1983: Relevance of mixed layer scaling for daytime dispersion based on RAPS and other field programs. *Atmos. Envir.*, **17**, 854–871.
- , S. T. Shipley, E. V. Browell, and D. A. Brown, 1984a: Cumulus cloud venting of mixed layer ozone. *Proc. Quadrennial Ozone Symp.*, Halkidiki, Greece, 9.9–9.11.
- , E. E. Uthe, B. M. Morley, and W. Viezee, 1984b: An observational study of transport in the free troposphere. *Proc. Fourth Joint Conf. Applications of Air Pollution Meteorology*, Portland, American Meteorological Society/APCA, 154–157.
- Clark, T. L., G. J. Ferber, J. L. Heffter, and R. R. Draxler, 1984: Cross Appalachian Tracer Experiment (CAPTEX-83). *Proc. Fourth Joint Conf. Applications of Air Pollution Meteorology*, Portland, American Meteorological Society/APCA, 158–161.
- Danielsen, E. F., 1961: Trajectories: Isobaric, isentropic and actual. *J. Appl. Meteor.*, **18**, 479–486.
- Lamb, R. G., 1983: A regional scale (1000 km) model of photochemical air pollution; Part I. Theoretical formulation. EPA-600/3-83-035, ESRL/ORD. [Available from U. S. Environmental Protection Agency, Research Triangle Park, NC 27711.]
- Rowland, J. R., and T. G. Konrad, 1979: A new technique for the study of power plant plume behavior using fluorescent dye as tracers and lidar as the remote sensor. Applied Physics Lab. Tech. Rep. SIR79U-003, Johns Hopkins University.
- Uthe, E. E., 1983: Application of surface based and airborne lidar systems for environmental monitoring. *APCA J.*, **33**, 1149–1155.
- , W. Viezee, and B. Morley, 1984: Airborne lidar monitoring of fluorescent dye particles as a tracer to characterize transport and dispersion: A feasibility study. Final Rep., EPA Contract 68-02-3791, SRI International, 118 pp. [Available from SRI International, Menlo Park, CA 94025.]